EuroCircol – Cosine Theta

Preliminary design of a 16T cosine theta bending dipole for the Future Circular Collider

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EuroCirCol A key to New Physics

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Outline:

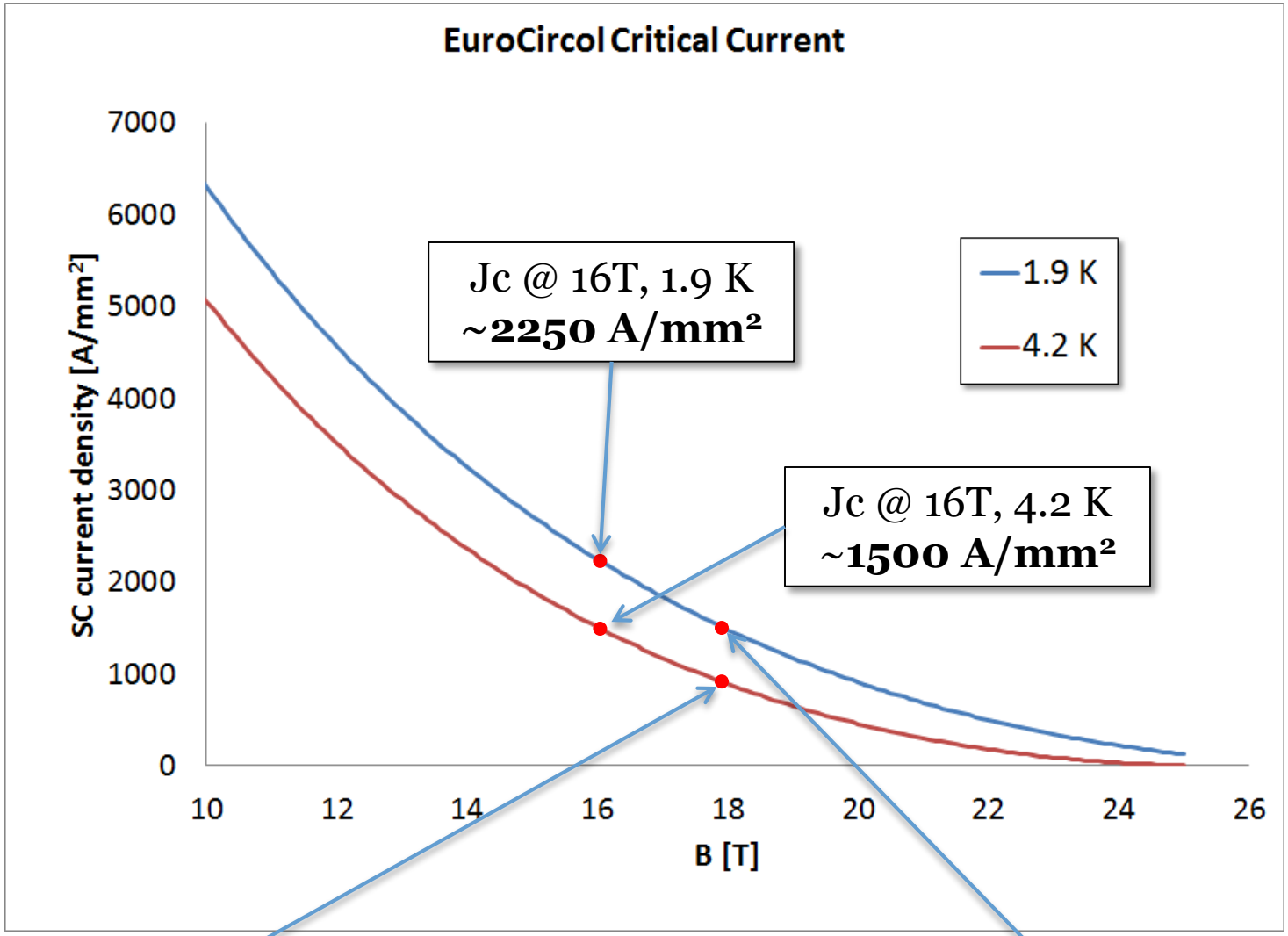
1. Main design parameters
2. Magnetic design
3. Mechanical design
4. Protection
5. Conclusions

1.1 Main design parameters

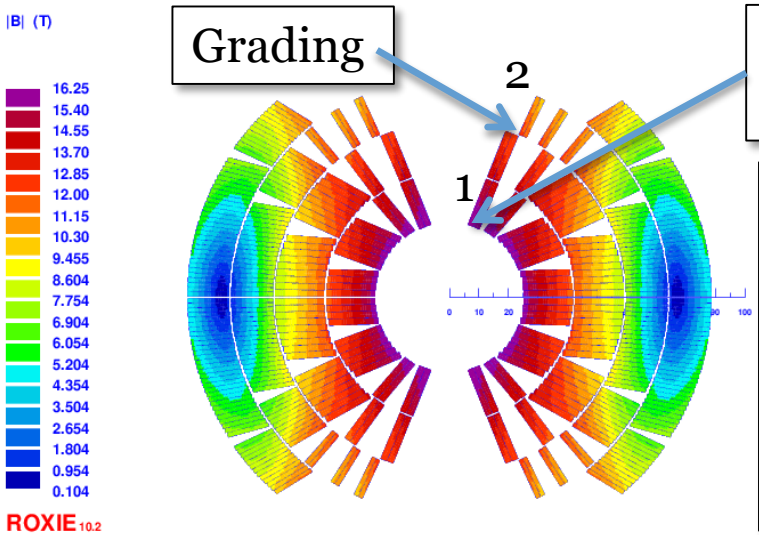
Constraints for the magnet design	
Bore inner diameter	50 mm
Beam distance	250 mm
Bore nominal field	16 T
Operating temperature	4.2 K
Operation on the load line	90 %
Maximum strand number per cable	40
Cable insulation thickness	0.15 mm
Cu/NCu	≥1
Field harmonics (geometric/saturation)	≤3/10 units
Peak temperature (105 % of operating current)	350 K
Yoke outer radius	400 mm

- Magnetic design for a **double aperture** magnet
- Mechanical design for a **single aperture** magnet

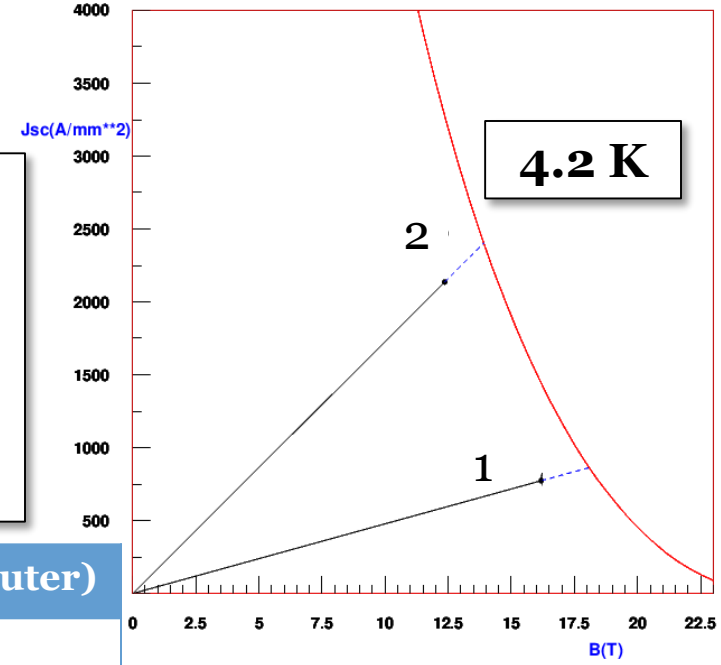
1.2 Main design parameters



2.1 Magnetic design – cross section



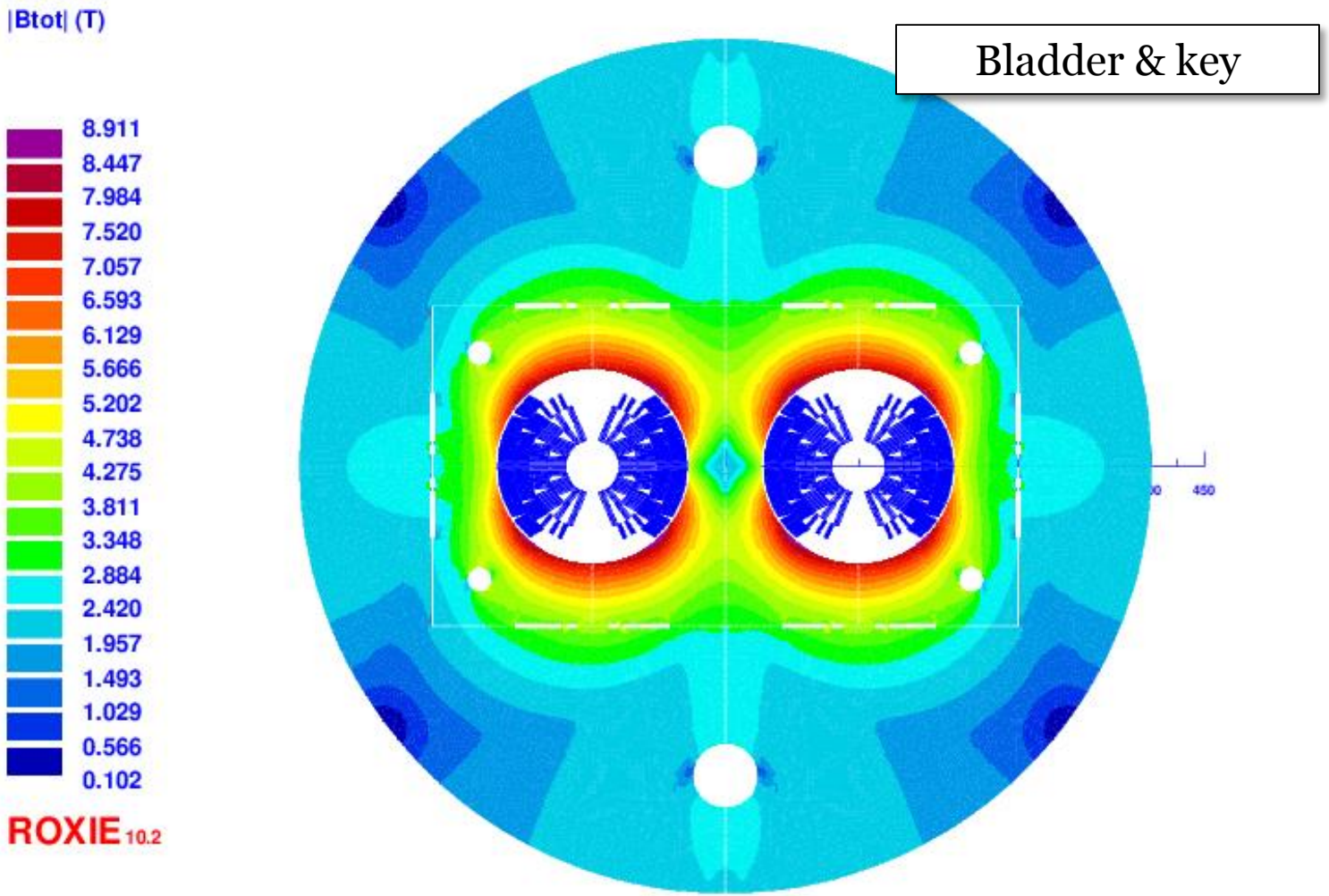
Turn number:
Layer 1: 14
Layer 2: 21
Layer 3: 37
Layer 4: 43
Tot: 230/ap.



	Cable 1 (inner)	Cable 2 (outer)
Strand number	28	38
Strand diameter	1.1 mm	0.7 mm
Bare width	16.5 mm	14 mm
Bare inner thickness	1.892 mm	1.204 mm
Bare outer thickness	2.036 mm	1.326 mm
Insulation	0.15 mm	0.15 mm
Keystone angle	0.5°	0.5°
Cu/NCu	1	2.04
Operating current	**10275 A**	**10275 A**
Operating point on LL (4.2 K)	**90 %**	**90 %**
Operating point on LL (1.9 K)	82 %	82 %

All the parameters are within the **designed constraints**

2.2 Magnetic design – iron yoke



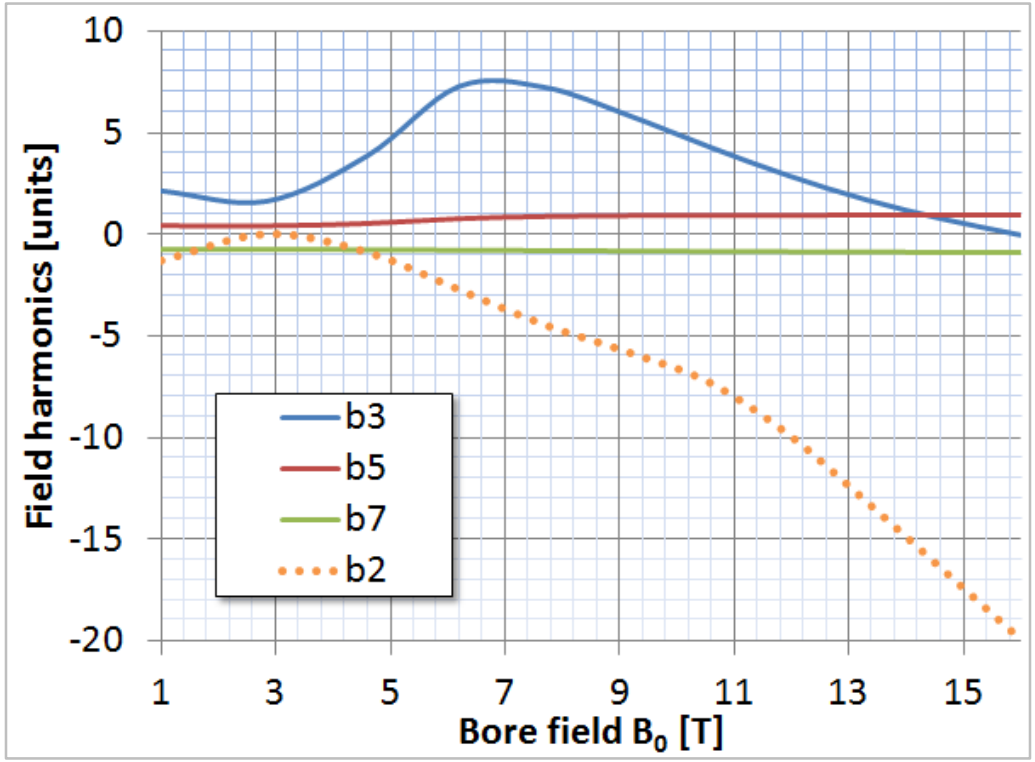
Inductance@I_{op} (1 ap)	Stored energy (1 ap)
25 mH/m	1.5 MJ/m

2.3 Magnetic design – field quality

NORMAL RELATIVE MULTIPOLES @ 16 T:

b 1: 10000	b 2: -19.94	**b 3: -0.01**
b 4: -0.49	**b 5: 0.97**	b 6: -0.01
b 7: -0.87	b 8: -0.00	b 9: 0.28
b10: 0.00	b11: 0.66	b12: 0.00
b13: -0.13	b14: 0.00	b15: 0.03

- b2 optimization <u>not yet performed</u>
- Persistent currents **not** considered



<u>Acceptable</u> field quality

2.4 Magnetic design – strand area

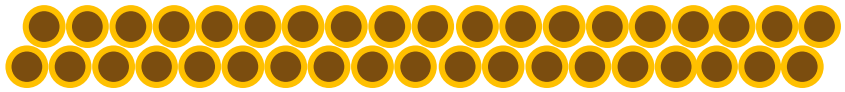
Conductor 1:

- 28 strands
- ∅ = 1.1 mm
- **Cu/NCu = 1**
- J_{cu} = 934 A/mm²
- Strand Area = 37.3 cm²/apert.
- Weight (FCC) = 4.3 ktons

Conductor 2

- 38 strands
- ∅ = 0.7 mm
- **Cu/NCu = 2.04**
- J_{cu} = 1047 A/mm²
- Strand Area= 46.8 cm²/apert.
- Weight (FCC) = 5.3 ktons

High Cu content for protection reasons!



COND. AREA (double ap.): = 168.1 cm²

FCC dipoles extrapolation:

➢ **COND. MASS: = 9.6 ktons**

Data for FCC extrapolation	
Number of dipole units	4578
Dipole lenght	14.3 m
Conductor density	8.7 kg/dm³

2.5 Magnetic design – strand area

- Option to <u>reduce cost</u>

Conductor 2 (smart option)

- 25 (**SC**)+13 (**Cu**) strands
- ∅ = 0.7 mm
- **Cu/NCu = 1**
- J_{cu} = 1047 A/mm²
- Strand Area (SC)= 30.7 cm²/apert.
- Strand Area (Pure Cu) = 16.0 cm²/apert.
- SC weight (FCC) = 3.50 ktons
- Pure Cu weight (FCC) = 0.75 ktons
- Pure Cu cost << SC cost

- Stability as in cable 1 (Cu/NCu = 1)
- Current diffusion time in the Cu strands to be evaluated and **compared with discharge time**
  - Zero order evaluation seems **ok** (few ms)

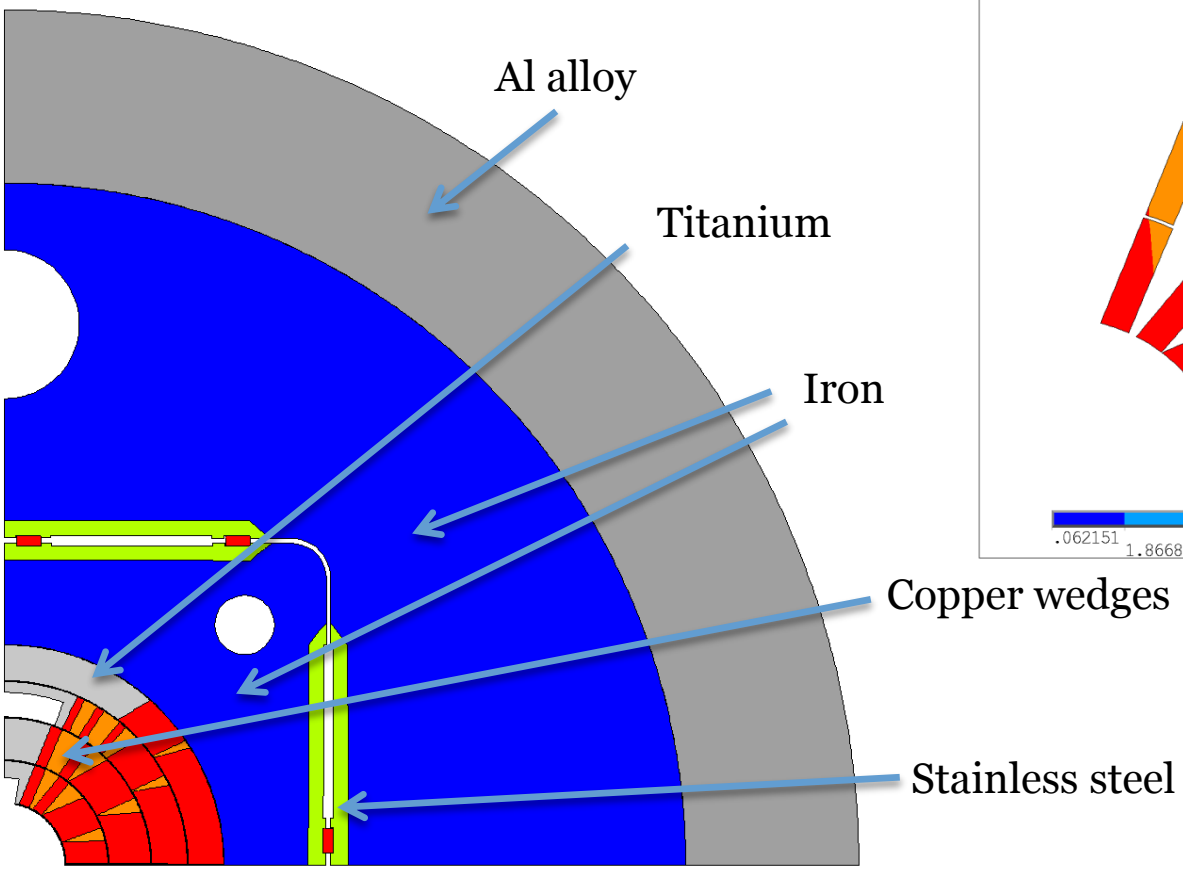
<u>TOTAL SC STRANDS:</u> = 9.6 → **<u>7.8 ktons</u>**

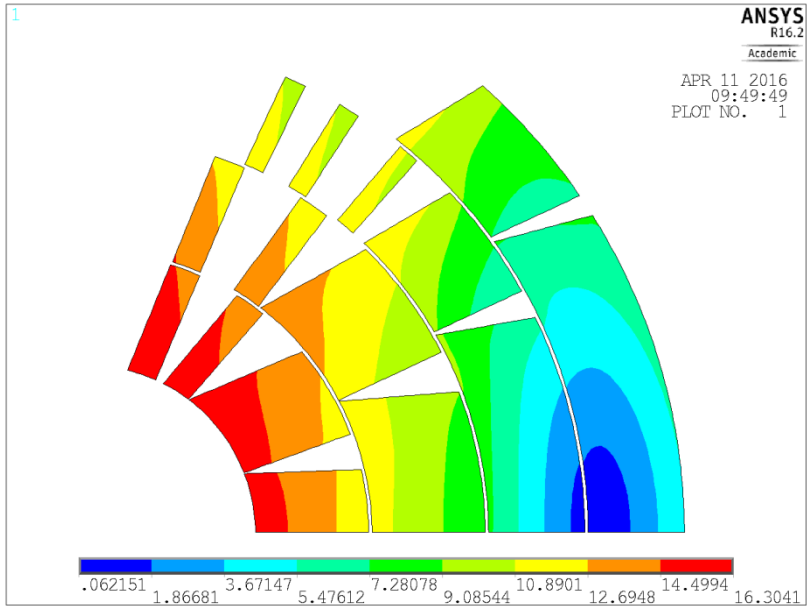
You can save

~20% costs

3.1 Mechanical design – layout

- The **mechanical** design of the cos-theta option presently <u>under study</u> exploit the **bladder & key** technology
  - It concerns a <u>single aperture</u> producing 16 T central field

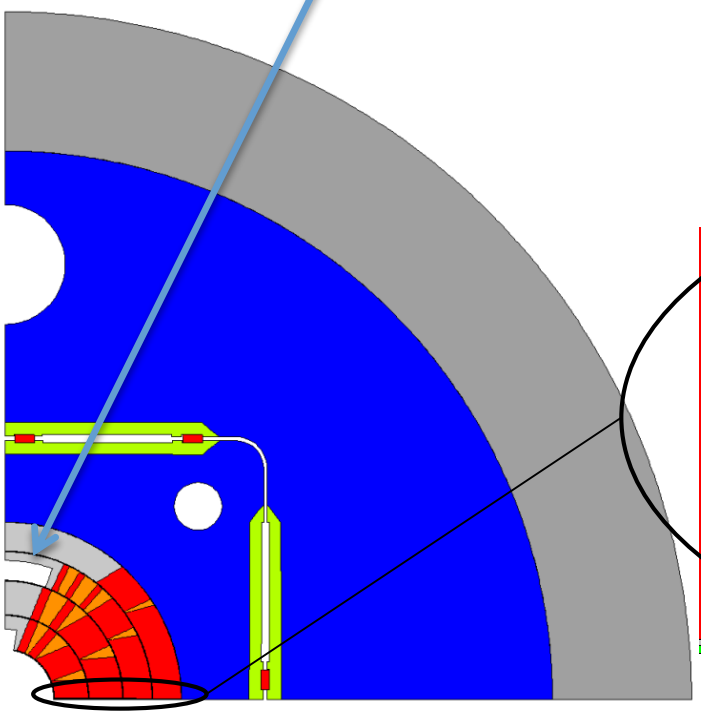


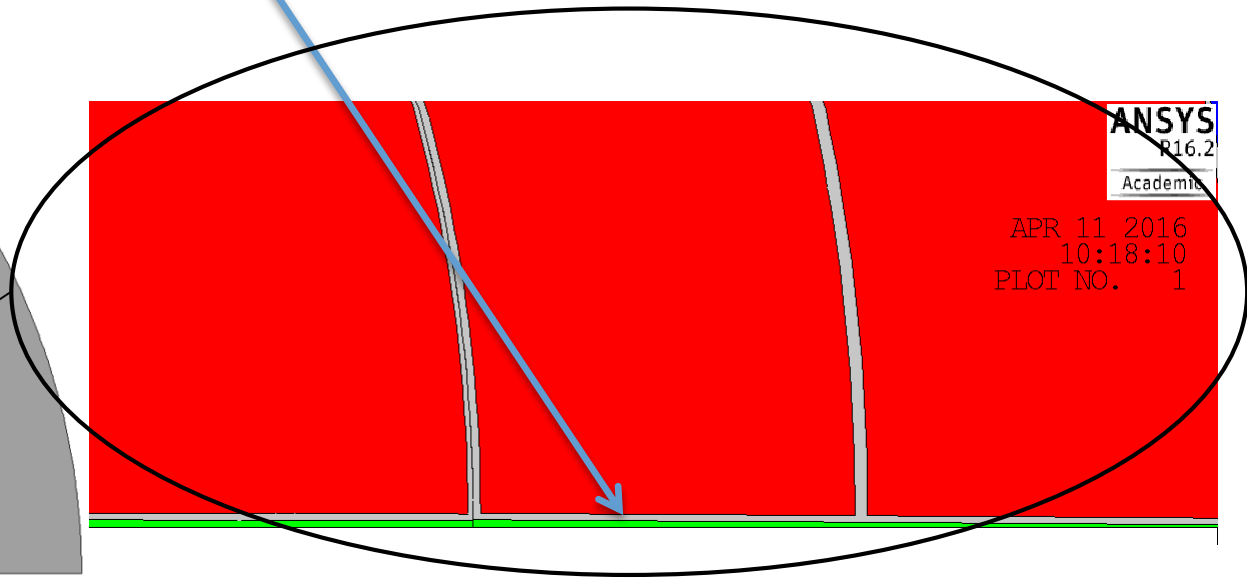


3.2 Mechanical design – layout

- Due to the very large Lorentz forces, the mechanical structure is based on **3 active elements**:
  - Standard **B&D** + Al alloy **shell** (70 mm thick)
  - Tapered **shim** on the midplane
  - Ti nose **undercuts**

azimuthal Lorentz forces		
	$\sigma_{\theta\,-layer}$ (MPa)	$\sigma_{\theta\,-winding}$ (MPa)
layer 1	77	125
layer 2	101	
layer 3	174	
layer 4	160	





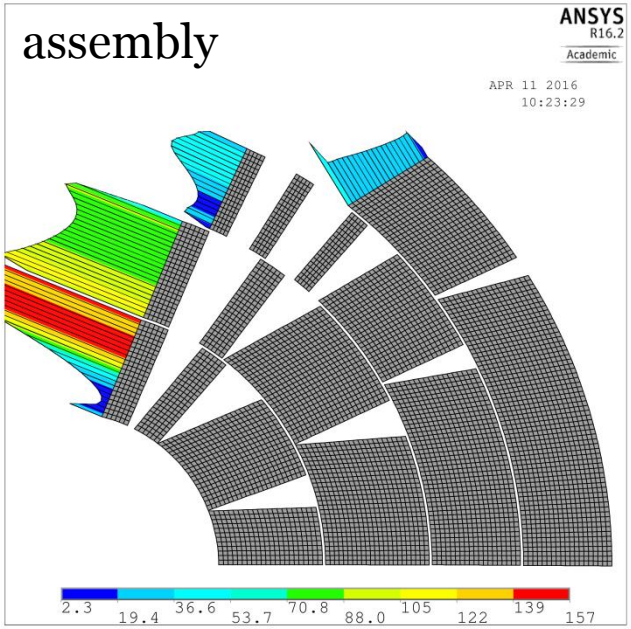
3.3 Mechanical design – accept. criteria

- The acceptance criteria are:
  - Pole-coil **contact** in pole-turns **midpoint**: $p_{cont} \geq 2$ MPa
  - Max bladder pressure < 50 Mpa
  - σ_{eqv} **coil** max ≤ **150** MPa at 293 K and ≤ **200** MPa at 4.2 K
  - All components σ_{eqv} ≤ stress limit
  - For iron at 4.2 K (brittle) $\boldsymbol{\sigma_1}$ ≤ ~200 MPa

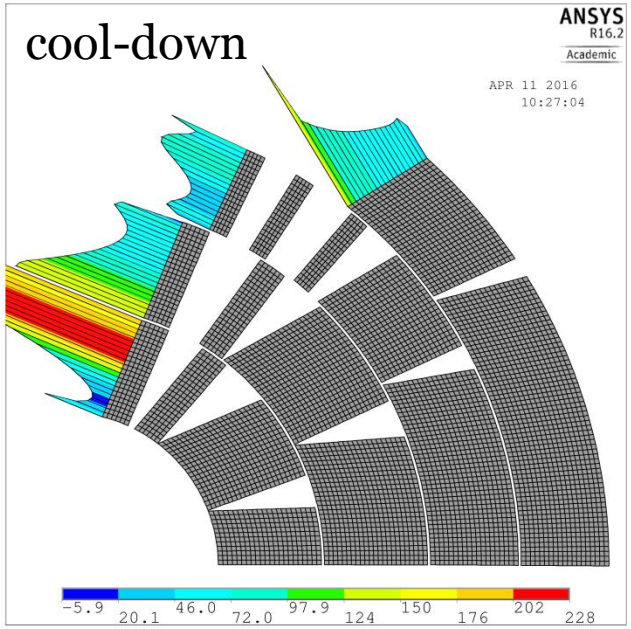
Material	Stress limit (MPa)		E (GPa)		ν	α
	293 K	4.2 K	293 K	4.2 K	293 K /4.2 K	293 K/4.2 K
Coil	150	200	EX=52 EY=44 GXY=21	EX=52 EY=44 GXY=21	0.3	X=3.1E-3 Y=3.4E-3
Austenitic steel 316LN	350	1050	193	210	0.28	2.8E-3
Al 7075	480	690	70	79	0.3	4.2E-3
Ferromagnetic iron	180	720	213	224	0.28	2.0E-3
Pole (Ti6Al4V)	800	1650	130	130	0.3	1.7E-3

3.4 Mechanical design – pole-coil contact

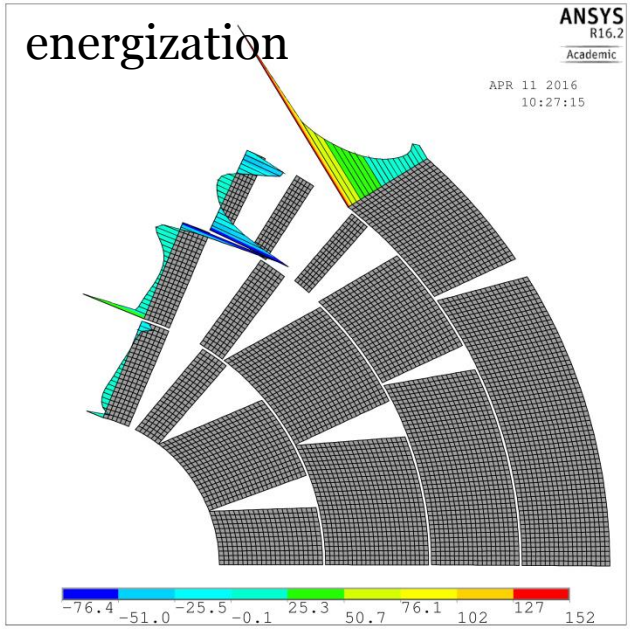
- The plots represent the <u>contact pressure</u> [**MPa**] at the **pole-coil interfaces**
  - Third layer is **not** optimal, even if in its **midpoint** $p_{cont} \geq 5$ MPa



Pressure [MPa]



Pressure [MPa]

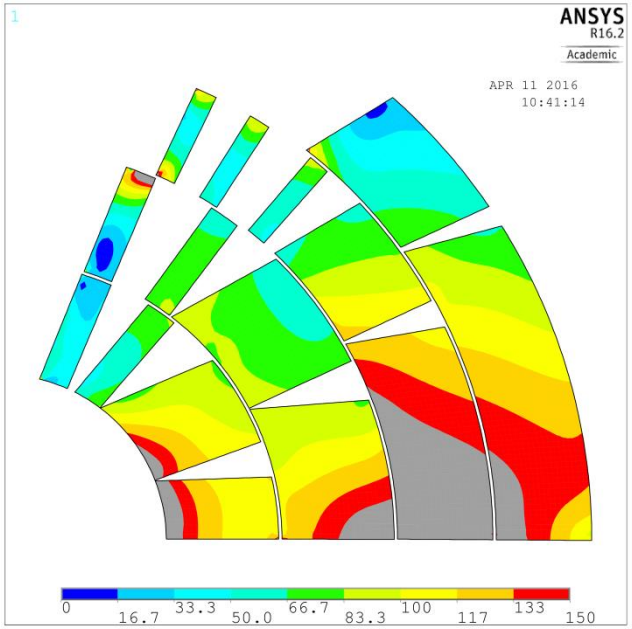


Pressure [MPa]

3.5 Mechanical design – Von Mises stress

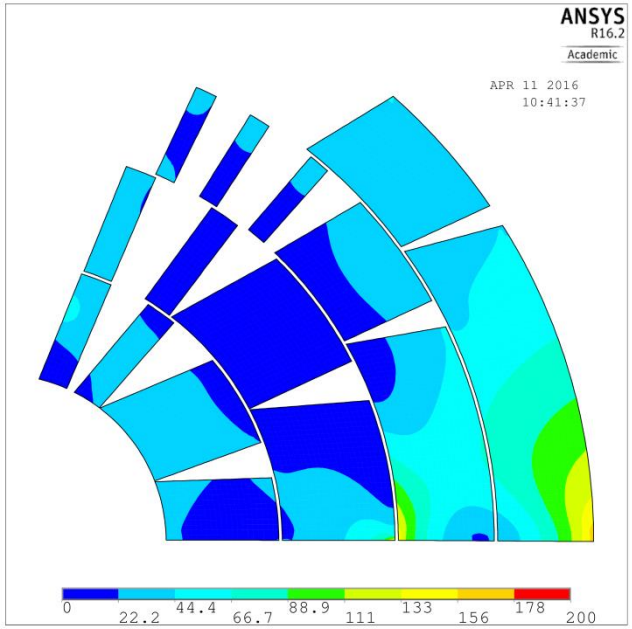
- The stress in the windings has **not been optimized** yet
  - The grey regions <u>overcome</u> **150** MPa at 293 K and **200** MPa at 4.2 K

assembly



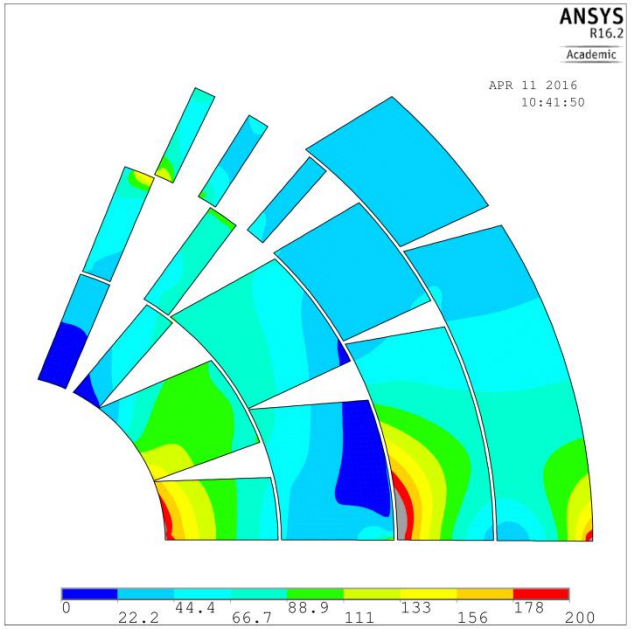
Pressure [MPa]

cool-down



Pressure [MPa]

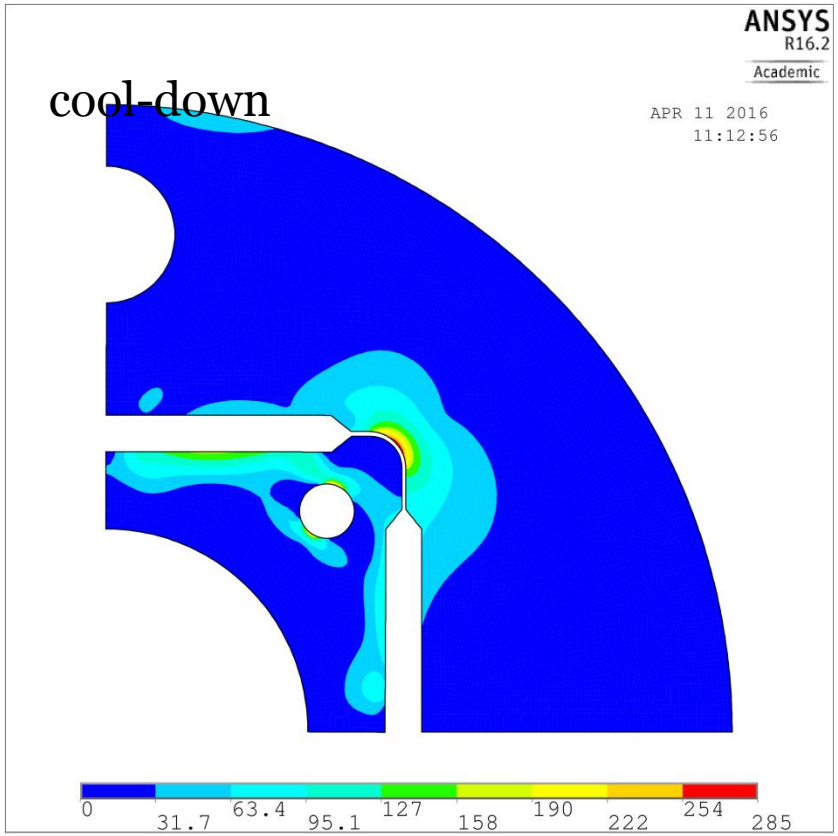
energization

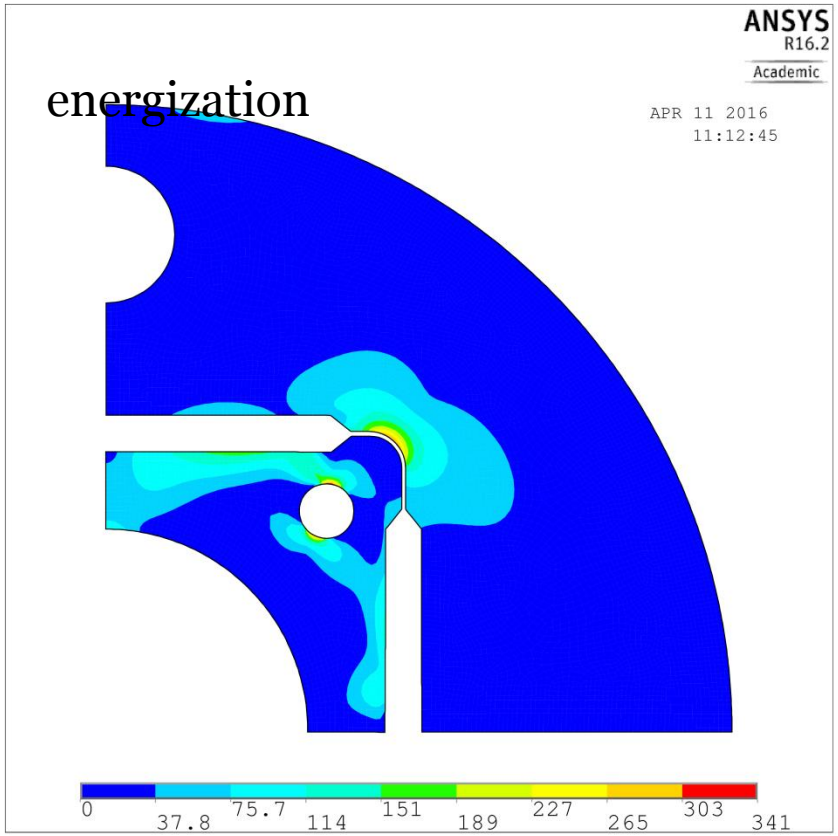


Pressure [MPa]

3.6 Mechanical design – σ1 in iron yoke

- At cold iron is supposed to become **brittle**. A safe condition is **σ1** <200 Mpa
  - The resulting stress can be limited by **increasing the curvature** radius where the peaks are located





3.7 Mechanical design – Von Mises stress in components

- Except iron, the Von Mises stress of all material is **below** the corresponding stress limit

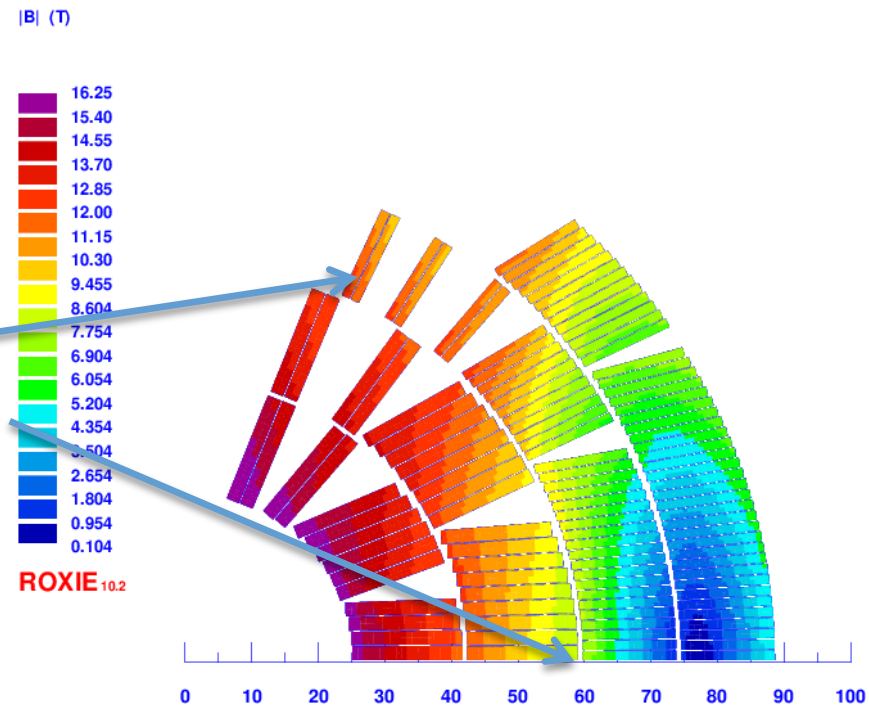
Material	Assembly [MPa]	Cool-down [MPa]	Energization [MPa]
Titanium	668	1150	613
Iron	381	451	553
Stainless steel	734	859	1010
Al alloy	47	168	167

4.1 Protection

Simulations from **Coodi** (Tiina Salmi)

- Main assumptions:
  - **No** energy extraction
  - Quench induced in the whole magnet **40 ms** after initial quench start
  - Inductance dependence on the current
  - Material properties from **NIST**

- Results (**105 %** of I_{op}):
  - Hot spot temperature: **~330 K**
  - Maximum voltage to ground: **~1400 V**



More details in the Tiina Salmi talk

5.1 Conclusions

- The presented 16 T cosine-theta **accomplishes** the **Eurocircol** design constraints
  - Margin on the load-line is **90%** at 4.2 K
  - Good **field quality**
  - Hot spot temperature **below 350 K** @ 105% I_{op}
- Main **cosine-theta advantage**: <u>less conductor area, less costs</u>
  - 168.1 cm²
  - Possibility of using **pure copper strands** in order to **save ~20%** of SC strands
- **Bladders and key** mechanical structure
  - Needed **pre-stress** can be <u>hardly achieved</u> @ I_{op}
  - Stress on the conductor **too high** in some zones, mainly during **assembly**
  - To be **improved**, <u>work in progress</u>